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AN ANALYSIS OF THE SKS SPLITTING AT SYOWA STATION IN ANTARCTICA

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Abstract: To reveal the seismic anisotropy of the crust and mantle beneath East Antarctica, we have conducted shear wave splitting analysis of SKS waves using STS seismograms at Syowa Station (69.01°S, 39.59°E). The obtained average direction of the fast shear wave was N49°E and the delay time was 0.7 s. This delay time was larger than the crustal values in other regions. As the origin of anisotropy in relation to large delay time, we consider three possible mantle flows: 1) present asthenospheric flow due to the plate motion, 2) paleo mantle flow related to Gondwana breakup, and 3) paleo mantle flow that has formed progressive metamorphism and foldings of the Lützow-Holm Complex in the Late Proterozoic. Neither the direction of present absolute plate motion (N120° E) nor the direction of first breakup of Gondwana at Syowa Station (NW-SE) coincides with the observed direction of anisotropy. From metamorphic studies, the compressional event related to progressive metamorphism has been recognized. The peak metamorphism has been observed along the thermal axis trending NW-SE. Other geologic fabrics around Syowa Station also show that this area has undergone NE-SW compression. We propose that the anisotropy is caused by lattice preferred orientation of mantle minerals along the NE-SW paleo mantle flow.

1. Introduction

To reveal the deformation properties in the global crust and mantle, study of seismic anisotropy, especially SKS splitting analysis, plays an important role. The analysis of SKS splitting has higher horizontal resolution than that of surface waves. Although the seismic structures in Antarctica have been discussed based on a few explosion experiments (*e.g.* IKAMI *et al.*, 1984) and surface wave dispersion (KNOPOFF and VANE, 1978/1979; ROULT and ROULAND, 1994; ROULT *et al.*, 1994), no shear wave splitting analysis has been conducted. We conducted shear wave splitting studies using broadband seismic data obtained at Syowa Station.

The SKS phase is characterized as a teleseismic shear wave once transmits into the outer core and it propagates as P wave within it. If a linearly polarized shear wave

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incidents into an anisotropic medium, the original shear wave splits into two orthogonal waves with different velocities as illustrated in Fig. 1. The SKS splitting analysis can provide the information on the anisotropic properties in the upper mantle and crust. This technique has two advantages over using direct *S* phases or *ScS* phases: (1) effects of anisotropy in the source side mantle before the core incidence can be ignored, and (2) polarization of the incident wave into the anisotropic region is simply in the radial direction, therefore, we have no need to calculate the source radiation pattern (Vinnik *et al.*, 1984). In this way, the SKS splitting analysis can map anisotropy of upper mantle even in a region of quiet seismicity.

The mechanism of upper mantle anisotropy is considered to be the lattice preferred

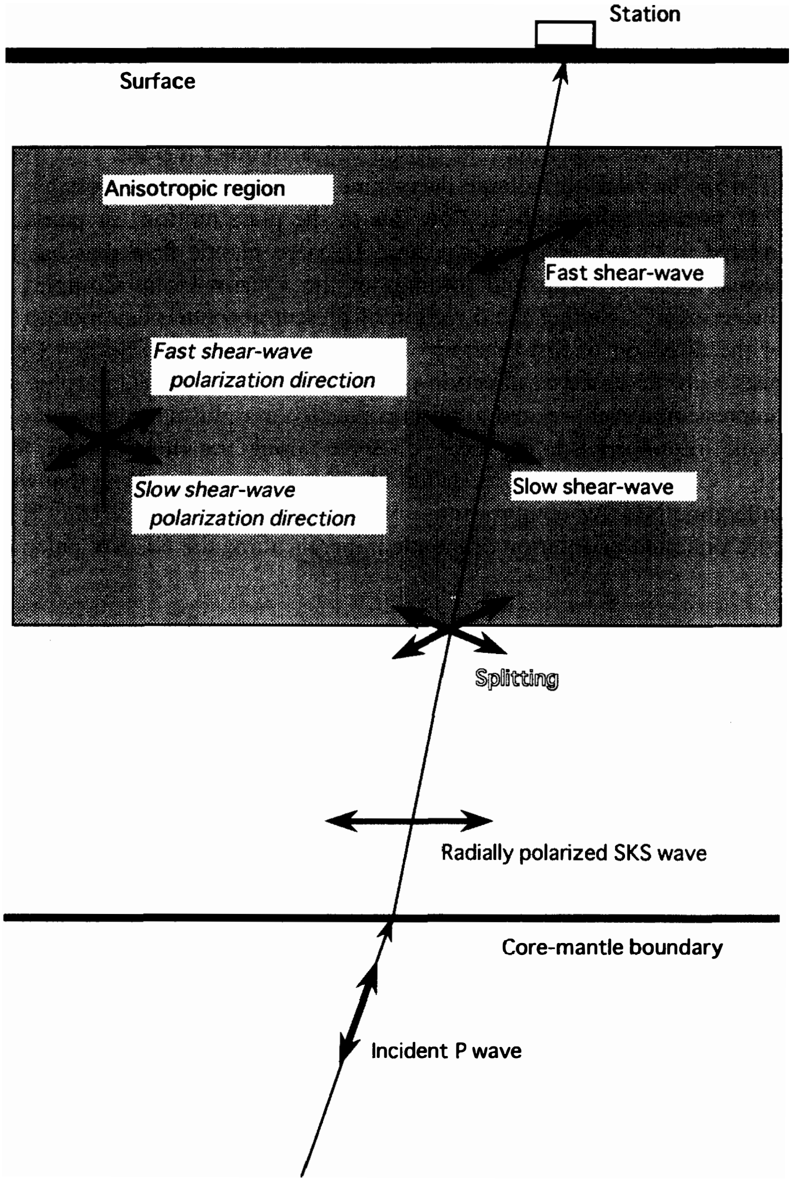

Fig. 1. Schematic setting of SKS splitting analysis on the cross section of Earth. The radially polarized SKS wave splits into two shear waves in the anisotropic region.

orientation (LPO) of olivine, pyroxene and other mantle minerals. Since the crystal axes are aligned in the direction of the mantle flow (Christensen and Salisbury, 1979), the fast directions of anisotropy are parallel to the spreading direction at ocean ridges and back arc basin (Raitt *et al.*, 1969; Katao, 1988). These directions are perpendicular to the maximum horizontal stress. The fast directions of anisotropy parallel to the strike of mountain belts (*e.g.* Makeyeva *et al.*, 1992) are observed, and they are also perpendicular to the maximum horizontal stresses. Although no clear relation to the primary mantle flow is indicated in the continental region, such anisotropy may possibly be formed by secondary mantle flows due to the collision of primary mantle flows.

In this study, we analyzed the SKS splitting in Antarctica using broadband seismic data obtained at Syowa Station. We discussed interpretations of strength of anisotropy and the relation between the fast directions of anisotropy and the directions of the possible paleo and present mantle flows.

2. Data

Broadband seismic observations using a Streckeisen Seismometer-1 (STS-1) at Syowa Station (69.01°S, 39.59°E, see Fig. 2) have been conducted since 1989. Continuous data of broadband velocity channels (BRB) have been recorded through 24 bit A/D converters with 0.1 s sampling rate (Kanao and Kaminuma, 1994). We selected the events located within the epicentral distances of 85°–125° from Syowa Station which were listed in JARE (Japanese Antarctica Research Expedition) Data Reports for 1990, 1991 and 1992 (Kami-

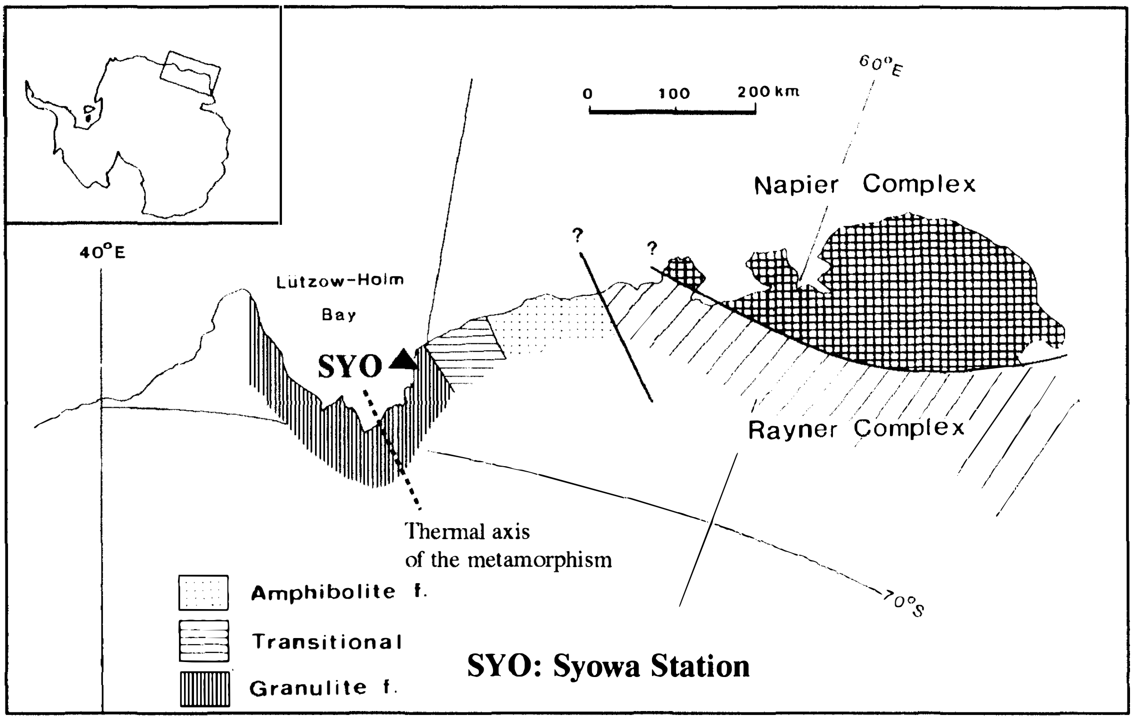

Fig. 2. Geological outline around Lützow-Holm Complex and location of Syowa Station (slightly modified from Motoyoshi et al., 1989). The location of thermal axis is from Hiroi et al. (1991).

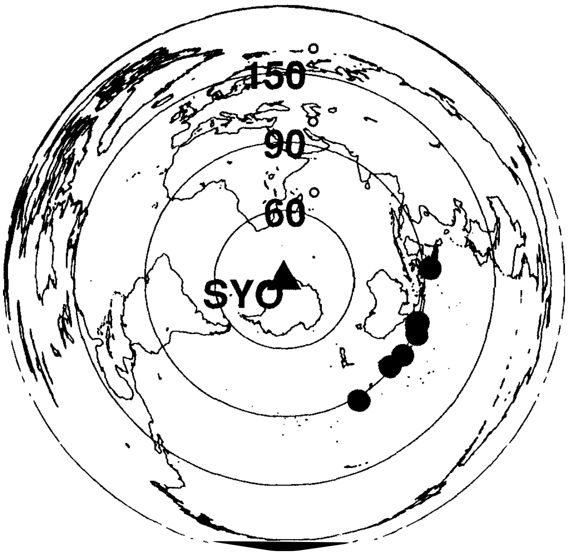

Fig. 3. Epicenters used to analyze SKS waves (solid circles) and location of Syowa Station (triangle) plotted by azimuthally equidistant projection.

Table 1. Event data used to analyze SKS splitting.

No.	y	m	d	h	m	s	Latitude (deg.)	Longitude (deg.)	Depth (km)	m_b
1	90	07	10	03	18	00.7	10.364 S	161.118 E	79	5.6
2	90	09	09	05	35	46.1	5.182 S	151.753 E	75	5.6
3	91	10	30	10	35	41.4	15.310 S	173.187 W	18	5.8
4	91	11	04	06	24	02.6	6.072 S	148.198 E	50	5.7
5	91	11	05	06	56	03.0	6.237 S	146.444 E	105	5.8
6	91	11	21	12	38	28.5	5.782 N	162.832 E	73	6.0
7	92	08	16	10	23	28.4	5.368 S	146.669 E	215	6.0
8	92	10	15	22	37	05.9	14.537 S	166.711 E	25	6.2
9	92	12	18	03	14	04.2	6.487 S	147.144 E	29	6.0
10	92	12	24	00	34	13.8	15.293 S	173.128 W	23	5.9

NUMA and NAGASAKA, 1992; KAMINUMA and YAMAMOTO, 1993; KANAO, 1994). For this distance range, SKS phases are clearly separated from S and other phases. The lower limit of body wave magnitude was set to 5.6 in our study to have a sufficient signal-to-noise (S/N) ratio.

Among 24 analyzed events, due to the S/N ratio, we adopted 10 events which occurred in the subduction zone from Tonga to Indonesia (Fig. 3, Table 1). These events cover a sufficient azimuthal range from 85° to 150° measured from Syowa Station to the epicenters (back azimuths).

3. Method

The shear wave splitting due to the propagation in a single anisotropic region can be described by two parameters: the direction of the fast shear wave and the arrival time difference between the two split waves (delay time). To estimate these two splitting parameters, we apply the method of minimizing transverse energy of reconstructed SKS seismograms just before incidence to the anisotropic region (SILVER and CHAN, 1988). This criteria is expressed by the following equation:

$$\min\{E_t(\phi,\ \delta t)\}=\min\left\{\frac{1}{T}\int_0^T \tilde{u}_t(\phi,\ \delta t,\ t)^2 dt\right\}\approx\min\left\{\frac{1}{N}\sum_{n=1}^{N}(\tilde{u}_{t,\,n})^2 \Delta t\right\}, \qquad (1)$$

where $\tilde{u}_t(\phi,\ \delta t,\ t)$ are time series data, which indicate the reconstructed transverse component of SKS waves as a function of rotation angle ϕ measured from north and time shift δt. Other parameters in eq. (1) are T: the time-window length analyzed, Δt: the sampling interval of digitized time series data and N: total data number of time series with the condition $N\Delta t = T$, respectively.

We searched for the most probable combination of ϕ and δt, which satisfies eq. (1) with intervals of 1° and 0.1 s, respectively. The error estimate of each combination of splitting parameters can be given by 95 % confidence level of F test which satisfies $Et/\min(E_t) = F_{0.05}(\nu,\ \nu)$, where ν is degree of freedom (for details, see SILVER and CHAN, 1988).

4. Results

An example of the contour map of $E_t(\phi,\ \delta t)$ for the No. 4 event in Table 1 is shown in Fig. 4 where the contour interval shows a difference between $\min(E_t)$ and critical E_t values at the 95% confidence level, which satisfy $E_t/\min(E_t) = F_{0.05}(\nu,\ \nu)$. The evident global minimum can be resolved and the corresponding splitting parameters are clearly

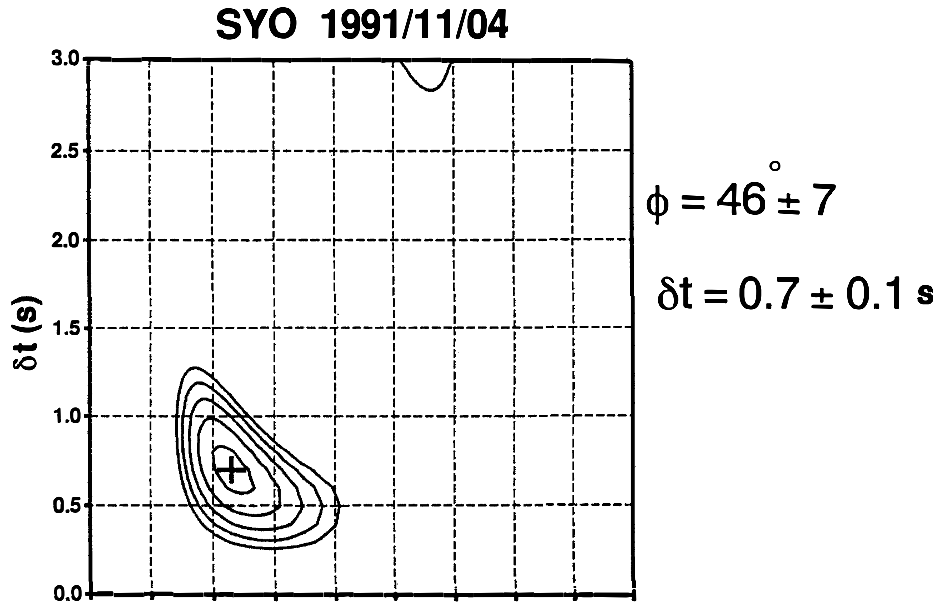

Fig. 4. Contour map of the calculated transverse energy as a function of variable splitting parameters. The vertical axis shows the delay time of two split waves, whereas the horizontal axis shows the fast direction of split shear wave. This contour is calculated for the event in the New Britain Region, No. 4 in Table 1. The contour interval is the difference between $\min(E_t)$ *and critical* E_t *values of 95% confidence level, which satisfy* $E_t/\min(E_t) = F_{0.05}(\nu,\ \nu)$.

obtained ($\phi = 46°$, $\delta t = 0.7$ s). Figure 5a shows the original SKS waveforms of horizontal components and their particle motions, while Fig. 5b shows reconstructed SKS waves after the correction by the obtained splitting parameters. The horizontal particle motion retrieves linear radial polarization, which shows adequate solution of the splitting parame-

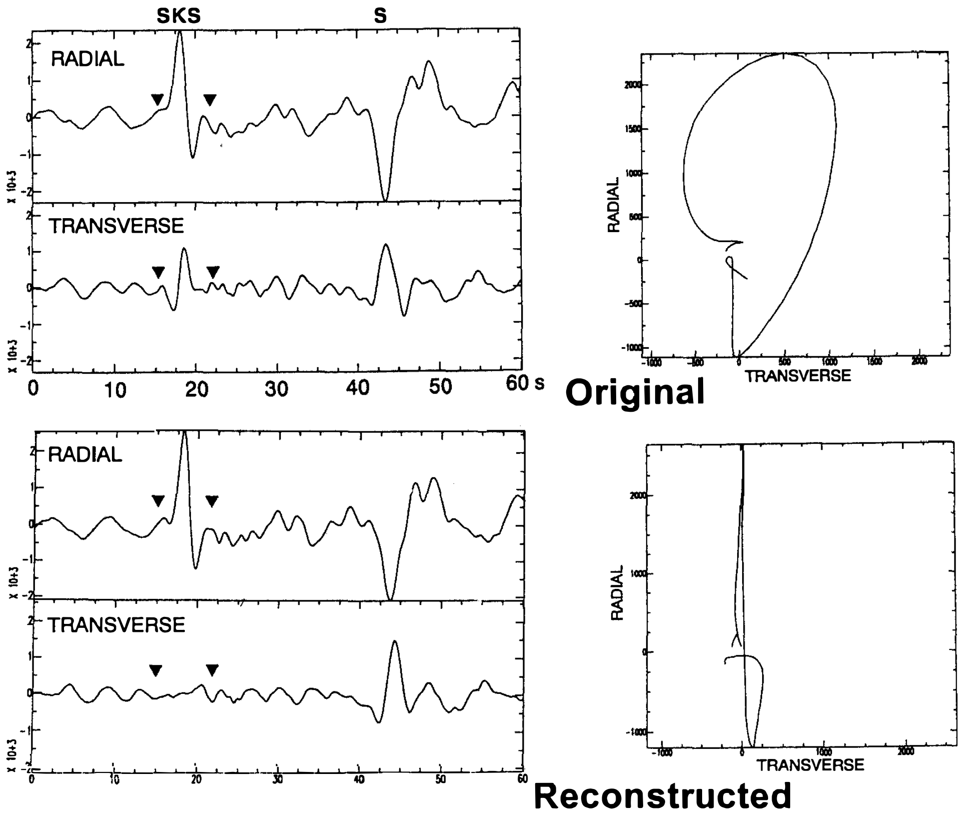

Fig. 5. SKS waveforms and the horizontal particle motions for both (a) original seismograms and (b) reconstructed SKS waveform by correction of the splitting parameters.

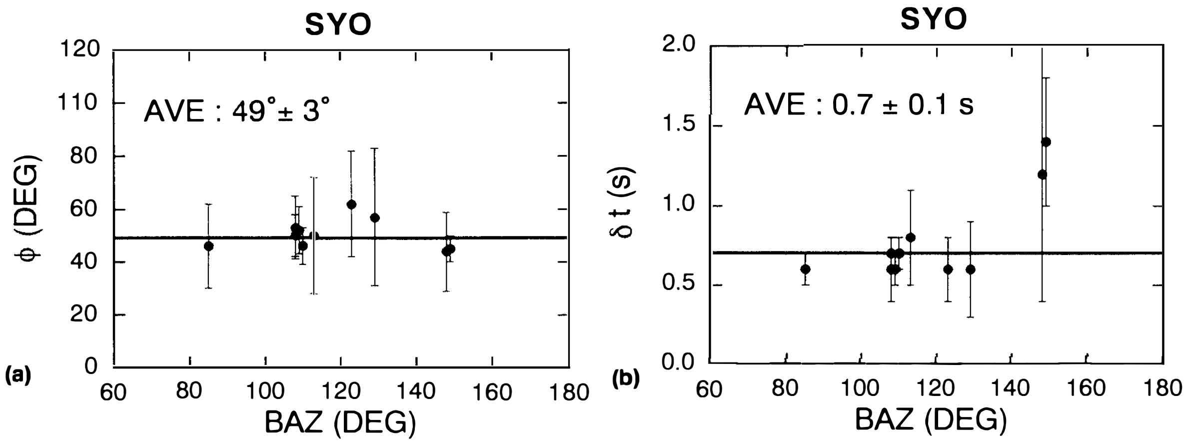

Fig. 6. Splitting parameters versus back azimuth of the analyzed events. (a) direction of fast SKS wave, ϕ (b) delay times, δt.

Table 2. Analyzed result for 10 SKS waves. Splitting parameters and their error estimates are listed.

No.	ϕ (deg.)	Err_ϕ (deg.)	δt (s)	$Err\_\delta t$ (s)	Back azimuth (deg.)
1	62	20	0.6	0.2	123
2	50	22	0.8	0.3	113
3	44	15	1.2	0.8	148
4	46	7	0.7	0.1	110
5	50	8	0.7	0.1	108
6	46	16	0.6	0.1	85
7	53	12	0.6	0.2	108
8	57	26	0.6	0.3	129
9	52	9	0.6	0.1	109
10	45	5	1.4	0.4	149
Average	49	3	0.7	0.1	

ters.

For all the events listed in Table 1, we estimated the most probable solutions of splitting parameters as illustrated in Fig. 6. The obtained fast directions of shear waves range from 45° to 60° with typical estimated error of 14°, while the delay times range from 0.5 s to 1.2 s with typical estimated error of 0.2 s. The results are also summarized in Table 2. The cause of biased results of delay times for the No. 3 and No. 10 events to larger values around 1.2 s are open to question. The weighted averages of all the splitting parameters (ϕ, δt) are N49°E and 0.7 s, respectively, where the weights are inversely proportional to the standard deviations for each solution. The error estimates of the weighted average are 3° and 0.1 s, respectively. As compared to typical delay times of SKS waves which show 1.2 s (SILVER and CHAN, 1991; VINNIK *et al.*, 1992), the result for Syowa Station shows relatively weaker anisotropy.

5. Discussion and Conclusions

When the direction of original SKS polarization is coincident with the principal direction of anisotropy, shear wave splitting may not happen, and we cannot estimate anisotropic properties. Sufficient coverage of the back azimuth distribution is required to obtain the precise result of shear wave splitting. Since the azimuthal distribution of our result covers almost one quadrant (85°-150°), the obtained results are not biased to any specific directional phenomenon.

The delay time at Syowa Station (0.7 s) shows smaller than 1.2 s, the global average result of SKS splitting analysis (SILVER and CHAN, 1991; VINNIK *et al.*, 1992). As for the crustal origin of anisotropy, BARRUOL and MAINPRICE (1993) indicate a theoretical upper limit of δt up to 0.2 s per 10 km thick crustal layer. However, the crustal anisotropy cannot explain the whole δt, because the observed crustal splitting seldom reaches 0.4 s (KANESHIMA, 1990; MCNAMARA and OWENS, 1993), even in a tectonically active region. Although the crustal anisotropy may partly contribute to the observed splitting, the significantly large delay time (0.7 s) must be explained as of mantle origin.

In general, the fast direction of anisotropy originating in the mantle shows direction of spreading in the ocean floor (Raitt *et al.*, 1969) or in a back arc basin (Katao, 1988). This is consistent with the LPO mechanism of mantle anisotropy. If the present horizontal mantle flow is active, the direction of fast velocity may coincide with the direction of absolute plate motion (APM). Vinnik *et al.* (1992) insist that the global distribution of directions of fast velocity found by SKS splitting studies reflects mostly APM directions. This positive correlation may come from the asthenospheric origin of the anisotropy due to LPO by horizontal mantle flow along the APM. However, at Syowa Station, the APM based on the HS2-NUVEL1 model (Gripp and Gordon, 1990) shows the direction of N120°E and velocity of 1 cm/yr, respectively, which direction is 70° different from the observed direction of fast velocity (Fig. 7a).

Another possible formation process of anisotropy may be related to breakup of the Gondwana Continent, because it was the major tectonic event in the region. In the first stage of the breakup, the spreading direction off Enderby Land was NW-SE (Nogi *et al.*, 1995). When mantle anisotropy is formed by this breakup, the presumed direction of fast velocity will also be directed to this spreading direction, however, this is perpendicular to the observed direction.

The geologic fabrics of East Ongul Island, where Syowa Station is located, have been investigated by Kizaki (1964). The surveyed area was slightly smaller than the wavelength of SKS waves (7-10 km). From his geological survey, the direction of maximum horizontal paleo-stress can be estimated to be between N50°E and N70°E (see Fig. 7b), which is consistent with the observed anisotropy from the splitting analysis. Motoyoshi *et al.* (1989) showed that the metamorphic grade of the Lützow-Holm Complex (LHC) increases toward the southwest (progressive metamorphism) (See Fig. 2). The thermal axis, which corresponds to the highest metamorphic condition, has nearly the same strike of the folding axis (NNW-SSE or NW-SE) at several tens of kilometers southwest of Syowa Station

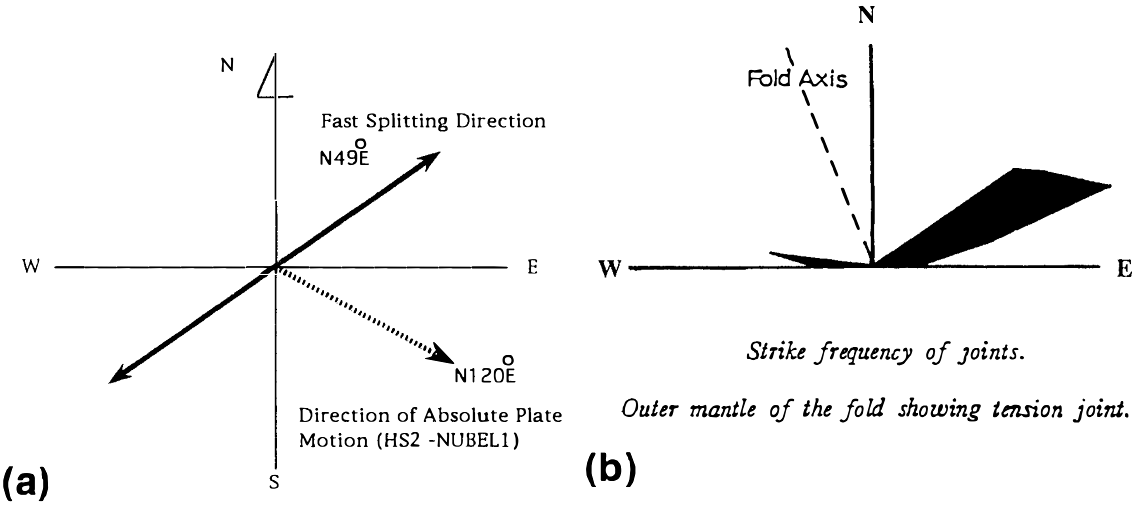

Fig. 7. Comparison direction of fast SKS waves with direction of plate motion or geological fabric direction: (a) direction of fast SKS wave and direction of absolute plate motion based on HS2-NUVEL1 at Syowa Station: (b) orientations of average fold axes and tension joints around East Ongul Island (cf. Kizaki, 1964).

(HIROI *et al*., 1991). The age of metamorphism is estimated to be 500 Ma (SHIRAISHI *et al*., 1992, 1994). If this region has undergone ENE-WSW or NE-SW compression, the related paleo mantle flow along this direction could have formed anisotropy which is related to the thermal axis of progressive metamorphism and foldings and joints.

In summary, the seismic velocity anisotropy beneath Syowa Station may not be due to the present asthenospheric flow, nor the past breakup of Gondwana. Since the fast direction of anisotropy coincides with the direction of compressional stress, which is also related to the regional progressive metamorphism of the Lützow-Holm Complex, we propose a mechanism of lattice preferred orientation along the mantle flow which caused NE-SW paleo compressional stress.

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